Signal Degradation in the Optical Fiber

Signal Attenuation

It determines the maximum unamplified or repeaterless distance between transmitter and receiver.

Signal Distortion

- Causes optical pulses broaden.
- Overlapping with neighboring pulses, creating errors in the receiver output.
- It limits the information carrying capacity of a fiber.

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Attenuation

The Basic attenuation mechanisms in a fiber:

1. Absorption:

It is related to the fiber material.

2. Scattering:

It is associated both with the fiber material and with the structural imperfections in the optical waveguide.

3. Radiative losses/ Bending losses:

It originates from perturbation (both microscopic and macroscopic) of the fiber geometry.

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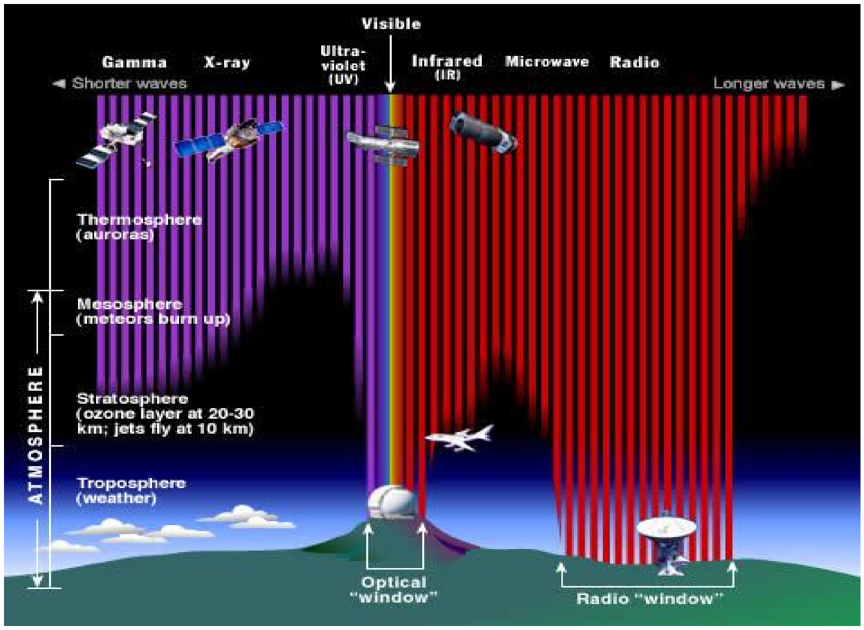
Example: Absorption by Atmospheric



Attenuation Units

If P(0) is the optical power in a fiber at the origin (at z=0), then the power P(z) at a distance z

$$P(z) = P(0)\, e^{-\alpha_p z}$$

$\alpha_p = (1/z) \ln [P(0) / P(z)]$ Fiber attenuation coefficient

Attenuation coefficient in units of decibels per kilometer, denoted by dB/ Km, then

$$\alpha(\text{dB/km}) = (10/z) \ln [P(0) / P(z)] = 4.343 \times \alpha_p (\text{km}^{-1})$$

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Q: Fiber has an attenuation of 0.4 dB/km at a wavelength of 1310 nm.
Then after it travels 50 km, what is the optical power loss in the fiber ?

Q: Optical powers are commonly expressed in units of dBm, which is the decibel power level referred to 1 mW. Consider a 30 km long optical fiber that has an attenuation of 0.4 dB/km at 1310 nm.

Find the optical output power P_{out}, if P_{in} is 200 μW

Absorption

Absorption is caused by three different mechanisms:

Absorption is caused by three different mechanisms:

1- Impurities in fiber material: from transition metal ions (must be in order of ppb) & particularly from OH ions with absorption peaks at wavelengths 2700 nm, 400 nm, 950 nm & 725nm.

2- Intrinsic absorption (fundamental lower limit): electronic absorption band (UV region) & atomic bond vibration band (IR region) in basic SiO2.

3- Radiation defects

Absorption

1. Absorption by atomic defects

Atomic defects are imperfections in the atomic structure of the fiber material.

Examples:

- Missing molecules
- High density clusters of atom groups
- Oxygen defects in the glass structure.

- Absorption losses arising from these defects are **negligible** compared with intrinsic and impurity absorption.
- Can be significant if the fiber is exposed to ionization radiations.

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Absorption

2. Extrinsic absorption by impurity atoms

The dominant absorption factor in silica fibers is the presence of **minute quantities of impurities** in the fiber material.

•These impurities include

- OH- (water) ions dissolved in the glass.
- Transition metal ions, such as iron, copper, chromium and vanadium

Origin :

OH ion impurities in a fiber preform results mainly from the **oxyhydrogen flame** used in the hydrolysis reaction of the $SiCl_4$, $GeCl_4$ and $POCl_3$ starting materials.

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Absorption

3. Intrinsic absorption by the basic constituent atoms

Intrinsic absorption is associated with the basic fiber material (e.g pure SiO_2).

Intrinsic absorption results from:

1. Electronic absorption bands in the ultraviolet region
2. Atomic vibration bands in the near infrared region

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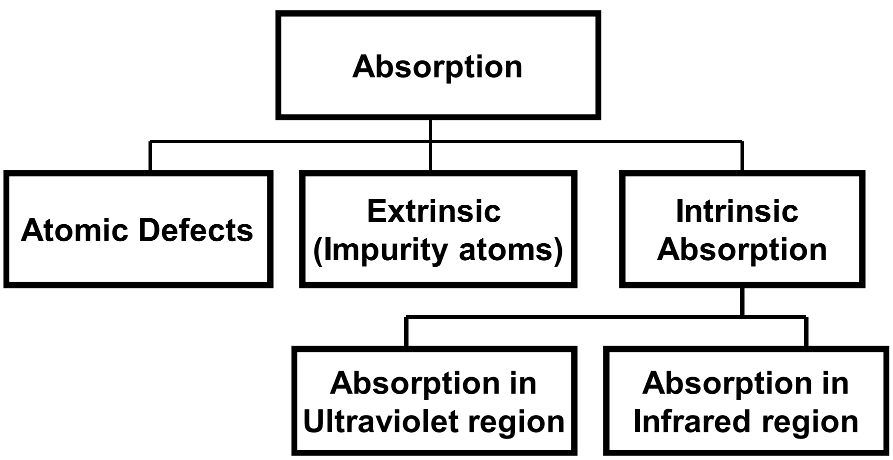

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Scattering Losses

Scattering losses in glass arise from **microscopic variation** in the material density from:

1. Compositional fluctuations
2. Inhomogeneities or defects occurring during fiber manufacture

These two effects give rise to refractive index variation, occurring within the glass over distances that are small compared with the wavelength.

These index variation case Rayleigh-type scattering of the light and inversely proportional to wavelength.

It decreases dramatically with increasing wavelength

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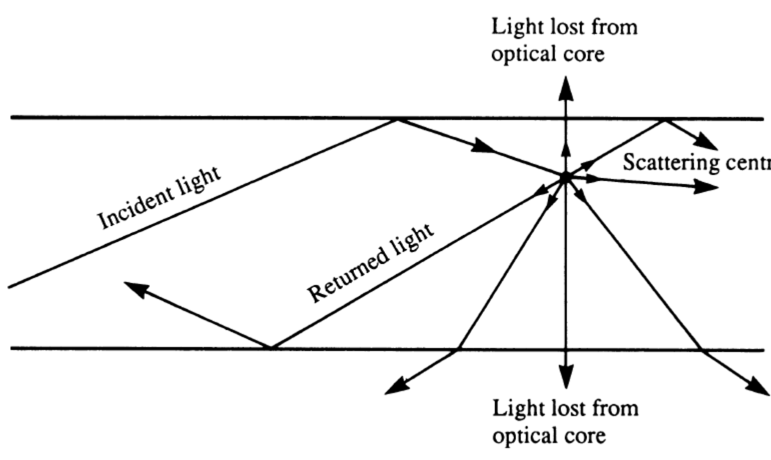
Scattering Losses



Rayleigh scattering in an optical fiber

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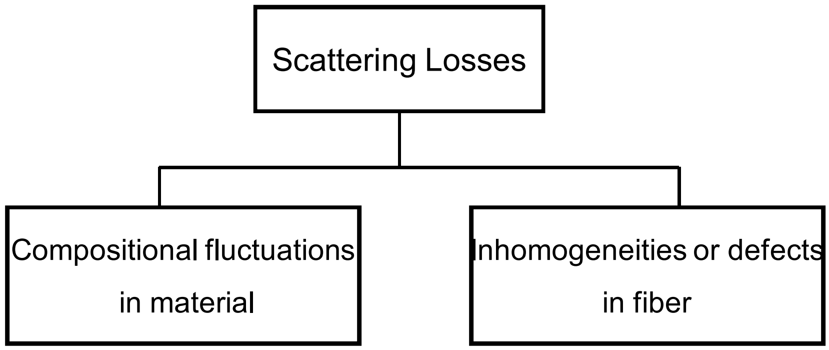


Radiative losses / Bending Losses

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature.

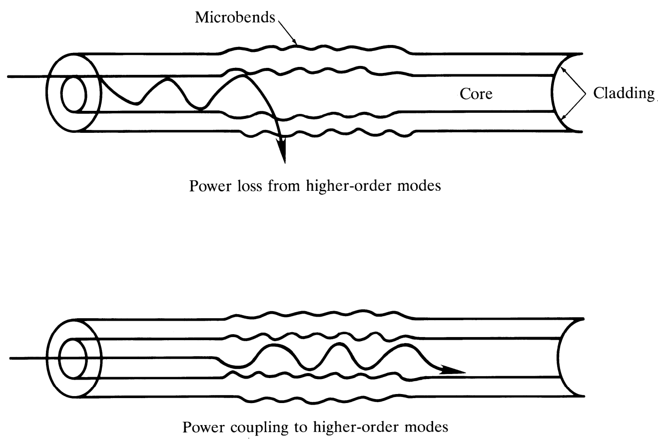
Fiber can be subject to two types of bends:

1. Macroscopic bends

2. Microscopic bends

Macrobending: Light lost from the optical core due to macroscopic effects such as tight bends being induced in the fiber itself.

Microbending. Light lost from the optical core due to microscopic effects resulting from deformation and damage to the core cladding interface.



Microbending losses

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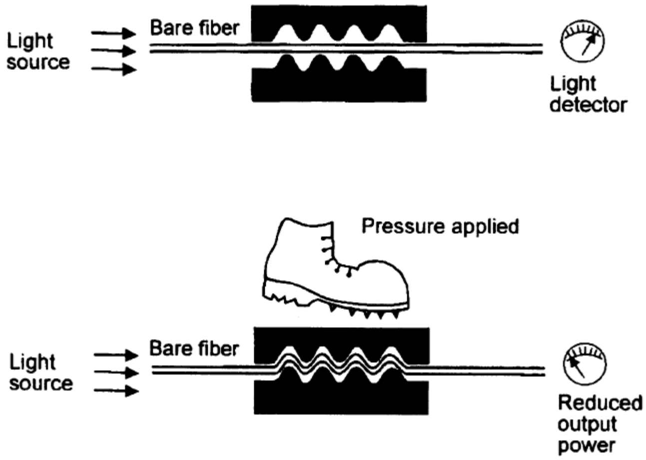

Pressure causes loss at the bends

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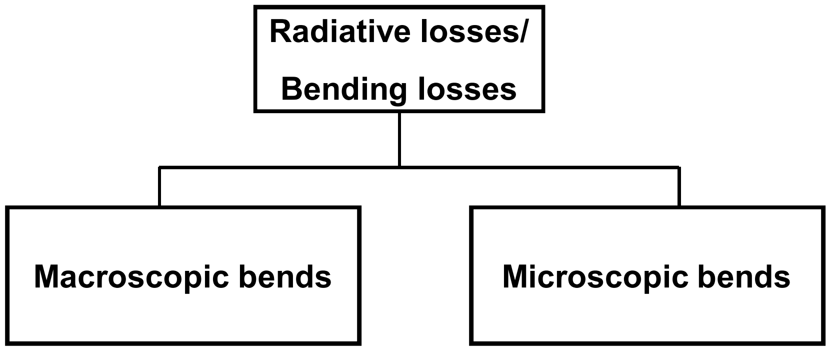

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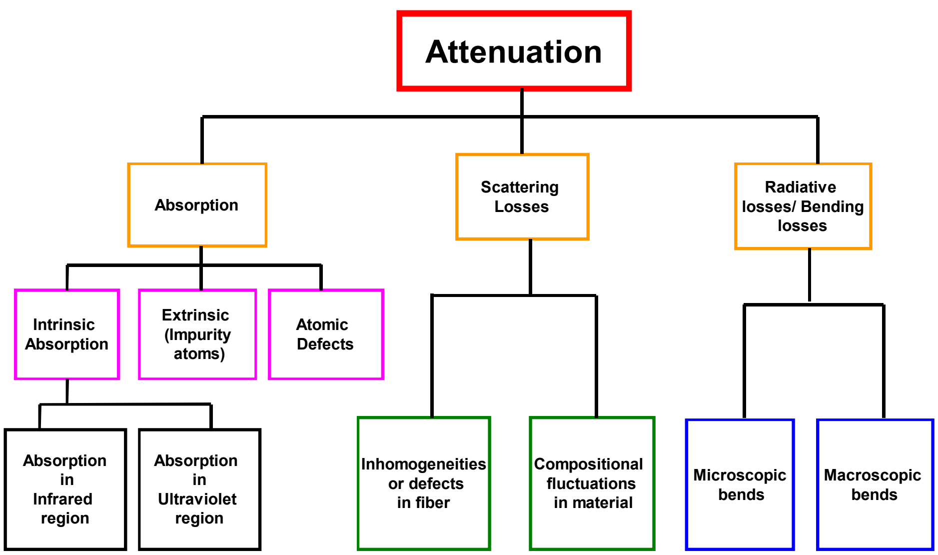

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Signal Distortion in Fibers

Optical signal weakens from attenuation mechanisms and broadens due to distortion effects.

Eventually these two factors will cause **neighboring pulses to overlap**.

After a certain amount of overlap occurs, the receiver can no longer distinguish the individual adjacent pulses and error arise when interpreting the received signal.

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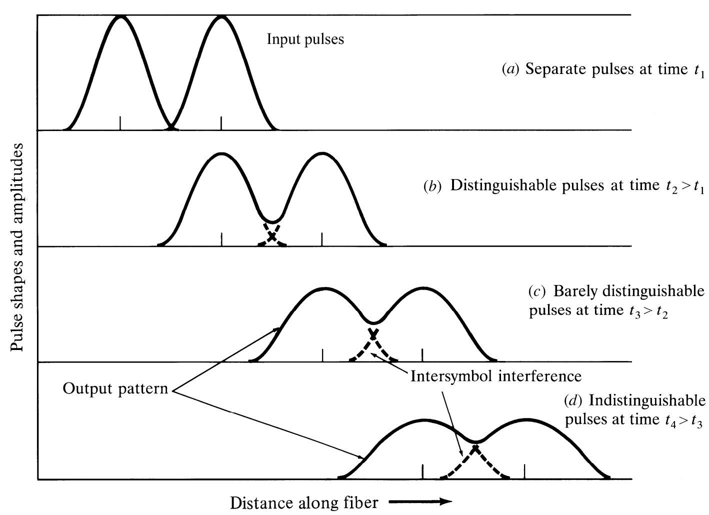

Pulse broadening and attenuation

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Dispersion

- The basic need is to match the output waveform to the input waveform as closely as possible.
- Attenuation only reduces the amplitude of the output waveform which does not alter the shape of the signal.
- Dispersion distorts both pulse and analog modulation signals.

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Dispersion

Dispersion results when some components of the input signal spend more time traversing the fiber than other components.

- In a pulse modulated system, this causes the received pulse to be spread out over a longer period.
- It is noted that actually no power is lost to dispersion, the spreading effect reduces the peak power.

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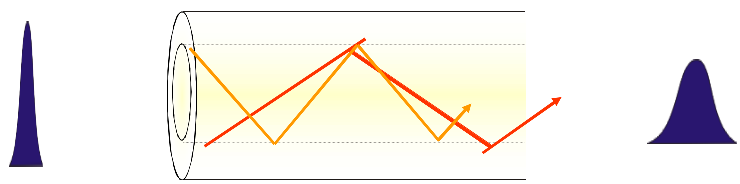
Dispersion

- Pulse dispersion is usually specified in terms of "Nanoseconds-per-kilometer".
- The difference in width of an input pulse with the width of the same pulse at the output, measured in time, is the dispersion characteristic for that piece of fiber.



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Dispersion

Dispersion of optical energy within an optical fiber falls into following categories:

- **Intermodal Delay or Modal Delay)**
- **Intramodal Dispertion or Chromatic Dispersion**
  - **Material Dispertion**
  - **Waveguide Dispertion**
- **Polarization –Mode Dispersion**

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Dispersion

Intermodal delay/ modal delay

Intermodal distortion or modal delay appears only in **multimode fibers**.

This signal distortion mechanism is a result of **each mode having a different value of the group velocity** at a **single frequency**.

The amount of spreading that occurs in a fiber is a **function of the number of modes** propagated by the fiber **and length of the fiber**

Group Velocity: It is the speed at which energy in a particular mode travels along the fiber.

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Intermodal delay/ modal delay

The maximum pulse broadening arising from the modal delay is the difference between the travel time T_{max} of the longest ray and the travel time T_{min} of the shortest ray .

This broadening is simply obtained from ray tracing for a fiber of length L:

$$\Delta T = T_{max} - T_{min} = n1/c \, (L/\sin ø_c - L) = (Ln_1^2/cn_2)\Delta$$

$$\Delta T = T_{max} - T_{min} = (Ln_1^2/cn_2)\Delta$$

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Intermodal delay/ modal delay

Fiber Capacity:

Fiber capacity is specified in terms of the **bit rate-distance** product **BL**.

(Bit rate times the possible transmission distance L)

For neighboring signal pulses to remain distinguishable at the receiver, the pulse spread should be less than 1/B.

Or

Pulse spread should be less than the width of a bit period.

$\Delta T < 1/B$ General requirement
$\Delta T \leq 0.1/B$ For high performance link

Bit rate distance product $BL < n_2 c / n_1^2 \Delta$

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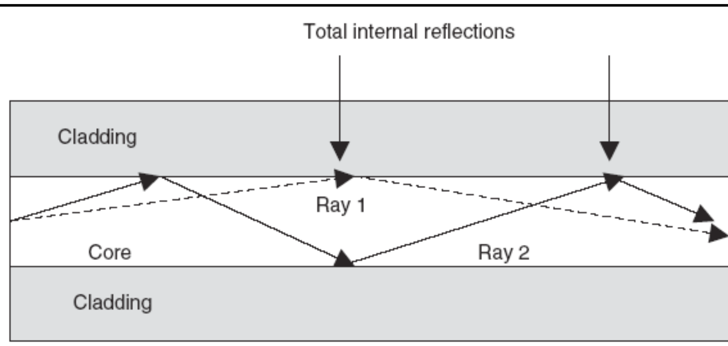
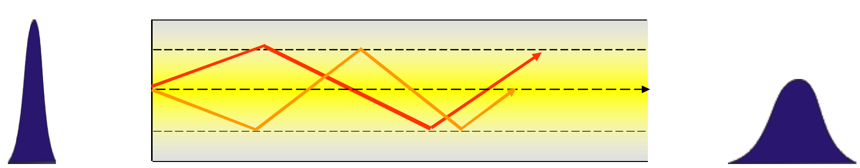


Light rays with steep incident angles have longer path lengths than lower-angle rays.



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How to minimize the effect of modal dispersion?

Answer is

1. Graded index fiber
2. Single mode fiber

How to get one mode and solve the problem

$$V = 2\pi a / \lambda \times (n_1^2 - n_2^2)^{1/2} = 2\pi a / \lambda \times (NA)$$

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How to get one mode and solve the problem

we could decrease the number of modes **by increasing the wavelength** of the light.

Changing from the 850 nm window to the 1550 nm window will only reduce the number of modes by a factor of 3 or 4.

Change in the numerical aperture can help but it only makes a marginal improvement.

We are left with the core diameter. **The smaller the core, the fewer the modes.**

When the core is reduced sufficiently the number of modes can be reduced to just one.

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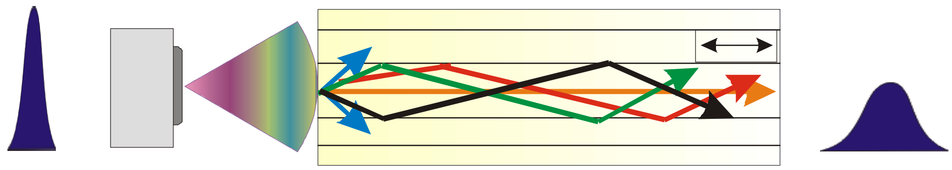

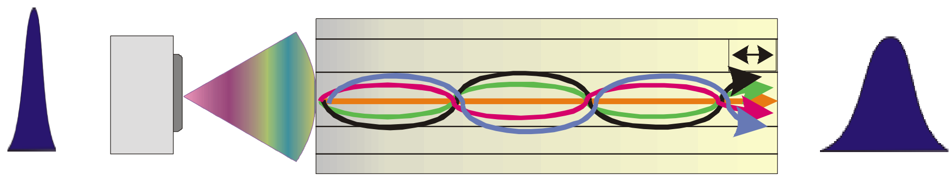

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Q: Consider a 1 Km long multimode fiber in which n_1= 1.480 and Δ = 0.10 , so that n_2= 1.465.

Then find ΔT= ?

Where:

L = 1 Km

n_1 = 1.480

n_2= 1.465

Δ = 0.10

$$\Delta T = (Ln_1^2/cn_2)\Delta$$

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Dispersion

Intramodal Dispersion or Chromatic Dispersion

This takes place within a single mode.

Intramodal dispersion depends on the **wavelength**, its effect on signal distortion **increases** with the **spectral width** of the light source.

Spectral width is approximately 4 to 9 percent of a central wavelength.

Two main causes of intramodal dispersion are as:

1. Material Dispersion
2. Waveguide Dispersion

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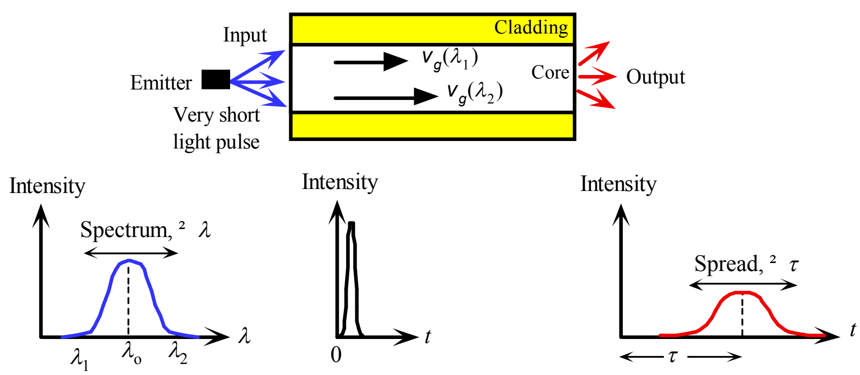
Material Dispersion



All excitation sources are inherently non-monochromatic and emit within a spectrum, $^2 \lambda$, of wavelengths. Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of n_1. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

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Intramodal Dispersion or Chromatic Dispersion

Material Dispersion:

This refractive index property causes a wavelength dependence of the group velocity of a given mode; that is,

Pulse spreading occurs even when different wavelength follow the same path.

Material dispersion can be reduced:

- Either by choosing sources with narrower spectral output widths OR
- By operating at longer wavelengths.

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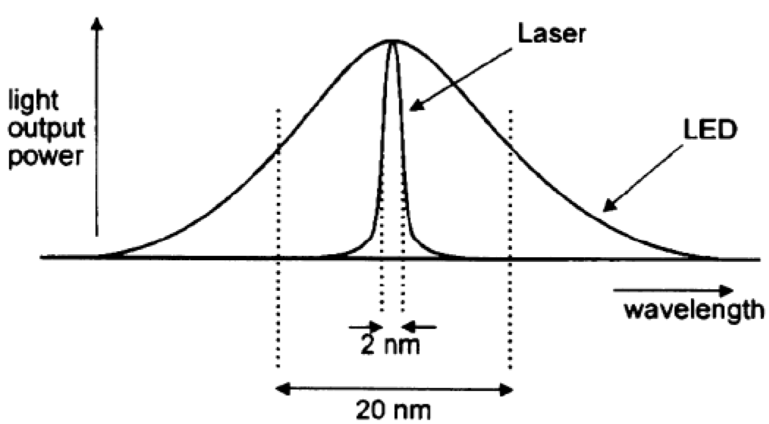

LASER source will produce far less **spectral dispersion or intramodal dispersion** than an LED source since it is more nearly monochromatic

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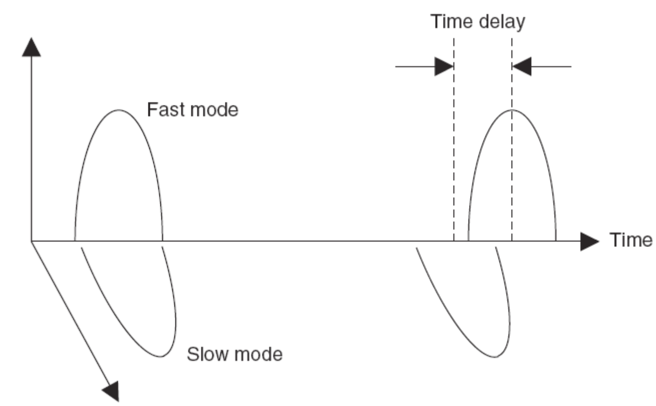

Variation in the polarization states of an optical pulse as it passes through a fiber that has varying birefringence along its length.

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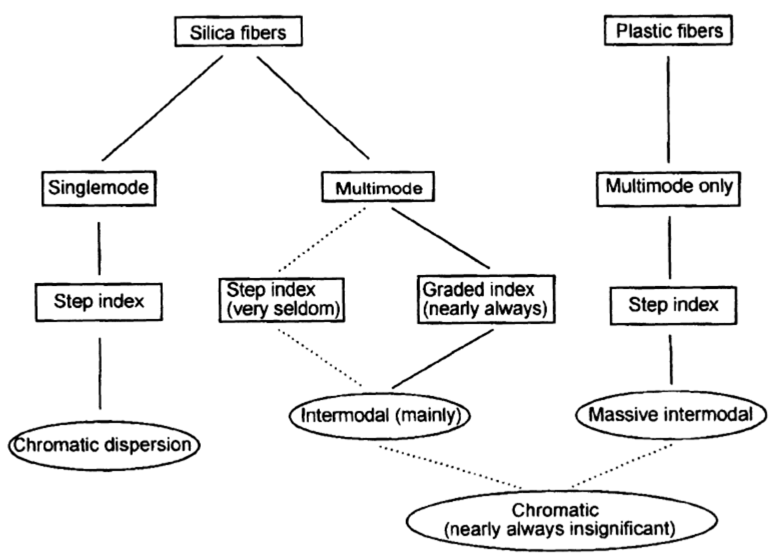

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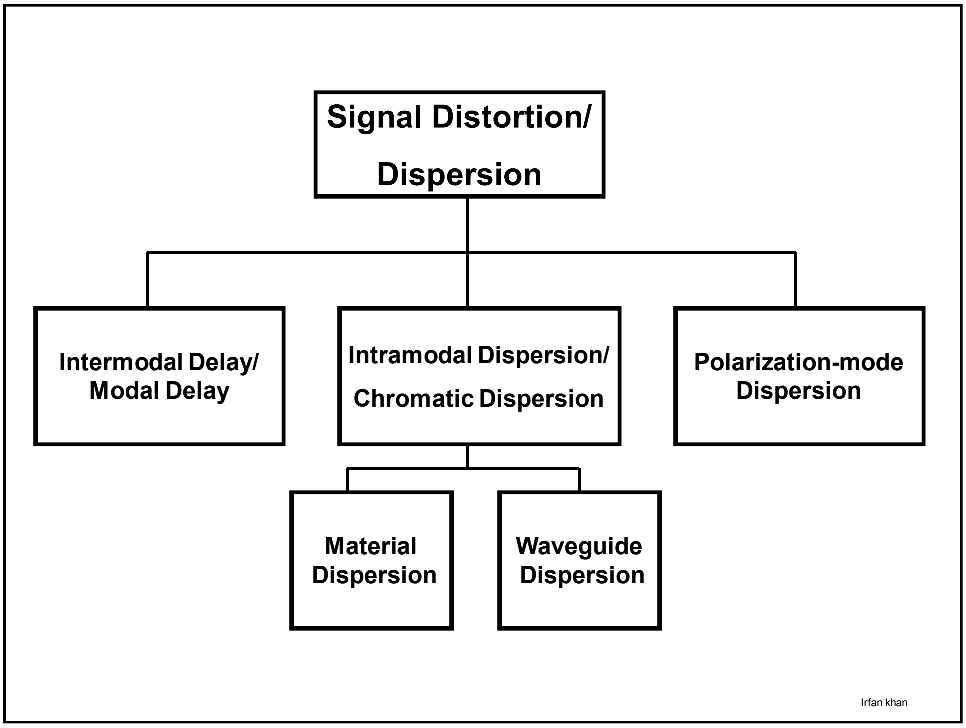
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Polarization-mode Dispersion
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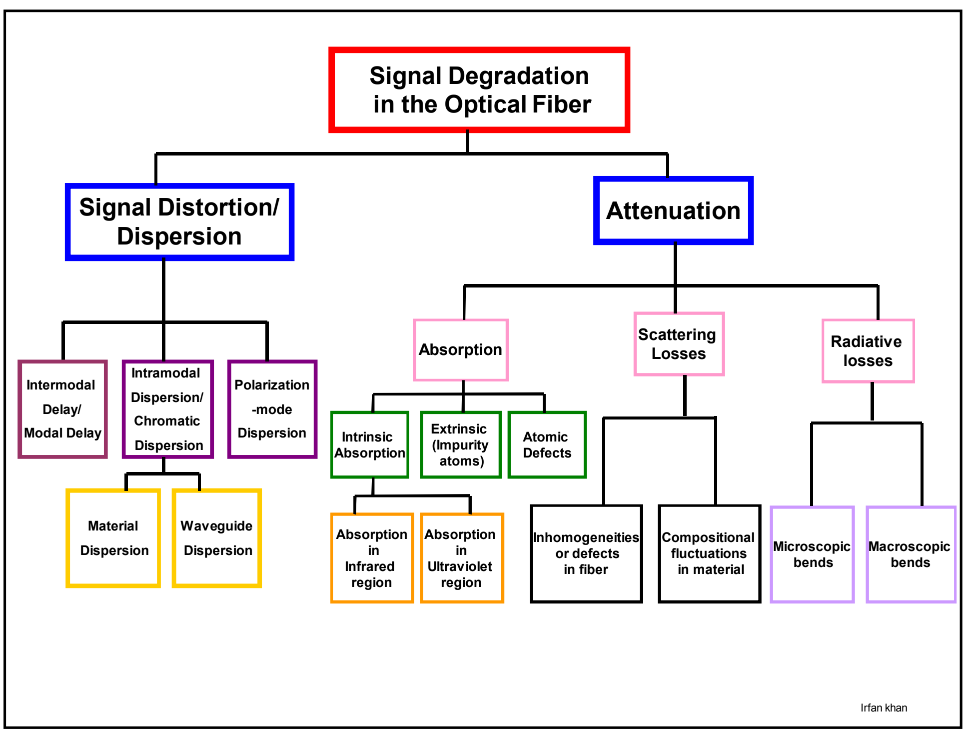
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Inhomogeneities or defects in fiber
Compositional fluctuations in material
Microscopic bends
Macroscopic bends
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